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Agency

Office of Emergency and
Remedial Response
Washington, DC 20460

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Superfund

EPA

Evaluation of Ground-Water Extraction Remedies

Volume 1
Summary Report

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Office of Emergency and Remedial Response
U.S. Environmental Protection Agency
Washington, DC 20460

Notice

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WDCR161/015.50

EXECUTIVE SUMMARY

Ground-water extraction is the most commonly used remedial technology for contaminated aquifers. In this investigation, information is assembled from hazardous waste sites throughout the United States showing how ground-water extraction systems are being used, how their performance compares with expectations, and what factors are affecting their success.

STUDY METHODS

The study is based on an information gathering effort consisting of two components. In the first component, general information was collected about hazardous waste sites where ground-water extraction is either planned or is already in use. This general data was obtained from EPA regional offices, state agencies, and environmental consultants. General data describing the site locations, the types of contaminants involved, the geologic nature of the sites, and the status of the remediations were collected for a total of 112 sites. Most of these sites were still in the pre-implementation phase or had generated such a short record of extraction system performance that no evaluation could be made. The 112 data base reports for these sites are bound separately as Volume 3 of this report.

The second component of the data gathering effort was to obtain detailed information on selected sites where ground-water extraction systems are already in operation. The information required included detailed descriptions of site hydrogeology and contaminant distributions, the design of the extraction systems and the analyses used in design, and data on the performance of the systems. Detailed information was obtained for 18 sites, and was used to prepare a series of 18 case studies, which are bound separately as Volume 2 of this study. Also included in Volume 2 is a 19th case study for a site in Canada that was prepared by the Environmental Ministry of Quebec.

STUDY FINDINGS

Trends identified from the 19 case studies lead to the following general conclusions[1]:

- The ground-water extraction systems were generally effective in maintaining hydraulic containment of contaminant plumes, thus preventing further migration of contaminants.

- Significant removal of contaminant mass from the subsurface is often achieved by ground-water extraction systems. When site conditions are favorable and the extraction system is properly

[1]The policy implications of these findings are discussed in a separate memorandum from the EPA's Acting Assistant Administrator of the Office of Solid Waste and Emergency Response (OSWER Directive 9355.4-03).

extraction systems. When site conditions are favorable and the extraction system is properly designed and operated, it may be possible to remediate the aquifer to health-based levels.

- Contaminant concentrations usually decrease most rapidly soon after the initiation of extraction. After this initial reduction, the concentrations often tend to level off and progress toward complete aquifer restoration is usually slower than expected.

- Data collection, both prior to system design and during operation, was frequently not sufficient to fully assess contaminant movement and the response of the ground-water system to extraction.

Three different remedial objectives have been identified for the ground-water extraction systems described in the case studies: aquifer remediation, migration control, and well-head treatment. Aquifer restoration for the purposes of this report means that the contaminant concentrations in the aquifer are to be reduced below specified levels that have been determined to be protective for the site. In the case of Superfund sites, the cleanup levels are either the regulatory Maximum Contaminant Levels (MCLs) or 10^{-4} to 10^{-6} excess cancer risk concentrations. Of the 19 sites studied in detail, 13 had aquifer restoration as their primary goal, and only 1 has been successful so far. Several of the other systems show promise of eventual aquifer restoration, but typically progress toward this goal is behind schedule. Concentrations often decline rapidly when the extraction system is first turned on, but after the initial decrease continued reductions are usually slower than expected.

The operational experience described in the case studies indicates that success in aquifer restoration depends on favorable aquifer and contaminant characteristics, and on appropriate system design. Sites that are favorable for aquifer restoration have relatively simple stratigraphy with fairly homogeneous unconsolidated aquifer materials and contaminants that are present primarily as dissolved constituents in the ground water. Most departures from these ideal conditions tend to impede the progress of aquifer restoration. However, even if the concentrations are not rapidly reduced to cleanup goals, the extraction systems may still significantly reduce contaminant mass in the aquifer.

Migration control, or plume containment, was the primary goal at 7 of the 19 case study sites. In some of these cases the systems were initially intended for aquifer restoration, but operating experience indicated that this goal was not feasible. Migration control is a less ambitious objective, but one that can be more easily attained. In all but three of the 19 case study sites, successful plume containment has been demonstrated. Failure to contain the contaminant plume has been definitely

Two of the sites described in the case studies involve well-head treatment. These are sites where water-supply wells have become contaminated, but have not been taken out of service. Instead, treatment systems have been installed at the wells to make the ground water produced suitable for its intended use. Both of the systems studied are successfully delivering water for domestic supply, and it appears that well-head treatment can usually be operated successfully. In addition to serving the primary need for water supply, these systems can often help to prevent the spread of contamination in the aquifer beyond the region already affected.

The design of an extraction system should be based on thorough analysis of the patterns of ground-water flow and contaminant transport that the system will produce. Frequently, the site information generated in pre-design investigations is inadequate to support the analysis necessary for optimal design. At a few of the sites studied, the administration of the remedial program was flexible enough to permit modification of the system in response to site information produced by performance monitoring.

The case studies also showed that monitoring of ground-water extraction system performance is frequently inadequate. Hydrologic monitoring is necessary for both aquifer restoration and migration control systems to ensure that the intended hydraulic capture zone is being maintained. Contaminant concentrations must be monitored by taking samples regularly from dedicated monitoring wells. Sampling the ground water produced from the recovery wells does not provide the information needed to evaluate the performance of ground-water extraction systems.

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Chapter 1
INTRODUCTION

1.1 PURPOSE OF THE STUDY

Ground-water extraction is the most commonly used remedial technology for contaminated aquifers. This method of remediation, also referred to as the "pump and treat method," usually includes three steps: (1) extraction of contaminated ground water from the aquifer via recovery wells, (2) treatment of the extracted water, and (3) disposal of the contaminants and discharge of the treated water. This study is concerned primarily with the first step in this process, the extraction of the contaminated ground water.

The specific goals of the study are:

1. To assemble information on how and where ground-water extraction is being used

2. To evaluate the performance of extraction systems at sites where operational experience is available

3. To investigate the design and operational considerations that have affected the performance of the extraction systems at these sites

As more experience has been gained with the long-term operation of ground-water extraction systems, it has become apparent that their performance often does not meet initial expectations. This is particularly true of systems that have been installed with the intention of cleaning up contaminated aquifers to health-based concentration goals. Cases where performance goals for aquifer cleanup have been met or exceeded are quite rare. As a result, questions have been raised concerning the general feasibility of aquifer remediation to health-based standards, how it is affected by site conditions, and how long remediation should be expected to take. This study has identified a few sites where ground-water extraction has either achieved the remediation goals or appears to be approaching those goals on schedule. More commonly, sites have been identified where progress toward remediation is lagging behind expectations, or the goal of remediation appears to be impractical and has been replaced with a containment objective.

Several physical phenomena have been identified that tend to interfere with the aquifer cleanup performance of extraction

systems. One of them is adsorptive partitioning of contaminants between the ground water and the aquifer materials. If adsorption in neglected, projections of extraction system effectiveness are likely to be over-optimistic. Aquifer heterogeneity can also reduce extraction system effectiveness by making it difficult to control the ground-water flow patterns in the area to be remediated. Aquifer cleanup where residual contaminant sources are present is difficult and often infeasible. Examples of residual contaminant sources include unremediated disposal areas, contaminated soils above the water table, and the presence of contaminants in a nonaqueous phase.

Aquifer restoration is not the only objective of ground-water extraction systems. Another commonly expressed goal is migration control, or hydraulic containment of the contaminant plume. In most aquifer restoration systems, plume containment is listed as a secondary goal. Indeed, it is usually necessary to establish control of contaminant migration if the aquifer is to be cleaned up. (Exceptions to this are sites where the aquifer can restore itself naturally by discharging to surface water bodies or through chemical or biological degradation of the ground-water contaminants.)

Another form of ground-water extraction, called the well-head treatment system, is sometimes found at well fields where production wells have become contaminated. Here it has been found to be cost-effective to continue producing contaminated ground water but to remove the contaminants by treatment before delivering it to the users. There are several variations of this approach. At some sites the source of the contamination is known, and an auxiliary extraction system has been installed there. This auxiliary system may be intended either to clean up the contaminated aquifer or simply to prevent continued migration toward the well field. In other cases, the source of the contamination may be unknown, and the well-head treatment system may be the only practical alternative.

1.2 STUDY METHODS

This is an empirical study based on the collection of information from actual ground-water contamination sites. It involves two separate but complementary data collection components: collection of general data on the use of ground-water extraction as a remedial technology, and detailed data collection for selected sites with operating ground-water

extraction systems. Information from the general data collection effort was used to select sites that were suitable for further detailed study.

1.2.1 Collection of General Data

The general data collection effort was intended to get a limited amount of information on a large number of sites. Its purpose was to provide general information on the locations of ground-water extraction sites, their remedial objectives, the hydrologic conditions and types of contaminants involved, the administrative programs controlling them, and the present status of the projects. The candidate sites for general data collection were not limited to those with operating systems, but also included systems that are still in the design or installation phase. However, information was not collected for sites contaminated by leaking fuel tanks or fuel spills. These sites were not included because they are so numerous and because the special problems associated with floating nonaqueous product deserve consideration at a level that is beyond the scope of this investigation.

Information was collected from EPA staff members involved with hazardous waste and RCRA sites as well as from state environmental protection offices in California, Florida, Minnesota, New Jersey, and New York. Contacts within the Army, Navy, Air Force, and Department of Energy were also queried for information about ground-water contamination sites on federal facilities. Additional sites were identified through professional contacts with environmental consultants, and reports in the open technical literature.

In Chapter 2, statistical descriptions of the results of this data collection effort are presented. The complete collection of database reports resulting from the effort is bound separately as Volume 3 of this report.

1.2.2 Collection of Detailed Site Data

The second data collection component involved the acquisition of detailed information on selected sites where ground-water extraction systems have been in operation long enough to produce a record of system performance. In this component of the study it was possible to draw at least tentative conclusions about the effectiveness of the extraction systems and the site-specific factors affecting them. On the basis of the information obtained a series of case studies has been prepared. These case studies are bound separately as Volume 2 of this report.

The detailed data collected for each site included background hydrogeologic information, the nature and history of onsite activities, the distribution and characteristics of ground-water contaminants, the design and operation of the extraction system, and progress reports on the effectiveness of the system. For those sites in the CERCLA program, the information was usually presented in RI/FS documents, remedial design reports, and quarterly, semi-annual, or annual monitoring reports on system operations. For RCRA sites, the information was often contained in Part B permit applications, and annual post-closure monitoring reports. For sites regulated by state agencies the information was presented in a variety of formats and was sometimes less than comprehensive.

One of the case studies included in Volume 2, for the Ville Mercier site in Quebec, was taken directly from the published proceedings of a technical conference. It is not the product of this study but has been included because of its applicability to the problems being investigated.

1.3 LIMITATIONS ON DATA COLLECTION

This study does not provide comprehensive coverage of all contamination sites where ground-water extraction is planned or in use. Because of time and resource limitations the general data collection effort had to rely heavily on the voluntary cooperation of individuals in state and federal environmental agencies. Responses to requests for assistance and data naturally varied from office to office and not all geographical or administrative divisions are covered equally. None-the-less, a representative cross-section of ground-water extraction sites seems to have been obtained.

Similarly, the sites selected for detailed case study do not include all of the operating extraction systems. Most of the sites identified in the general data collection effort were still in the pre-implementation phase, but of those systems that have begun operation, many have been in operation for such a short time that no substantial performance record has yet been generated. There are also some sites where ground-water extraction has been going on for a relatively long time, but the data collected is not sufficiently detailed for use in a case study.

Chapter 2
OVERVIEW OF RESULTS

2.1 GENERAL SITE DATA COLLECTION

The general site data collection effort obtained information on 112 sites where ground water extraction has been chosen as the remediation technique. This information was entered into a database using dBase III Plus software. The variety of sources from which the information was obtained caused some inconsistency. Data were entered as objectively as possible but some interpretation was necessary, for instance, when a narrative description was provided that did not fit neatly into the pre-selected database categories. Additional information on any of the sites may be available from the contact persons listed on the database reports in Volume 3.

A concise summary of the data collected for the 112 sites identified is presented in Table 2.1. The subsections that follow will discuss and present statistics on the data categories represented by the columns of the table.

2.1.1 Site Locations

Sites from all 10 EPA Regions are represented in the general data. In addition to sites located within the United States, data from one site in Canada and two sites in Puerto Rico were entered into the database. The distribution of the number of sites from each region is:

EPA Region	Number of Sites	Percent
I	6	5
II	13	12
III	8	7
IV	44	39
V	10	9
VI	10	9
VII	1	1
VIII	1	1
IX	6	5
X	12	11
Other	1	1
	112	

Table 2.1
SUMMARY OF GENERAL SITE DATA

SITE NAME	STATE	EPA REGION	Administrative Program						Remedial Objective					Extraction Type			System Enhancements		Site Type						Contaminant Type					NAPLS		Aquifer Materials								
			Superfund	RCRA	State Lead	DOD / DOE*	Other		Restoration	Containment	W.H. Treatment	NAPL Recovery	Leachate Col.	Wells	Well Points	Trenches	Pulsed Pumping	Reinjection	Underground Storage Tank	RIZ. Waste Dump	Industrial Plant	Ammunition Dump	Other		Organics	Metals	High Sorption	Low Sorption		Floaters	Sinkers	Clay	Silt	Silt/d	Gravel	Fractured Rock	Interbedded Sediments	Limestone	Other		Extraction	Begun
25TH STREET WELLFIELD	FL	IV					X			X				X										X				X												
AIR PRODUCTS & CHEMICALS	NJ	II			X				X					X				X			X			X				X	X			X	X						X	
AMCO	WV	III		X	X				X												X			X											X					
AMERICAN CYANAMID	WV	III					X							X							X			X		X														
AMERICAN CYANAMID	FL	IV		X					X	X				X							X			X				X					X	X						X
AMERICAN WOOD TREATING	MS	IV		X					X			X		X							X			X						X			X							
AMPHENOL	NY	II		X		X			X	X				X							X			X								X	X						X
ANDERSON CORPORATION	MN	V			X	X			X	X				X							X			X					X		X		X	X					X
ANNISTON ARMY DEPOT	AL	IV					X		X					X								X		X								X								
AREA D - MCCLELLAN AFB	CA	IX					X		X	X				X								X		X				X			X	X								X
BALDWIN POLE & PILING	AL	IV		X					X			X		X		X				X	X			X						X		X								X
BAYOU BONFOUCA	LA	VI	X							X	X	X		X									X	X					X	X		X			X					
BERKS SAND PIT	PA	III	X						X					X									X	X											X					
BF GOODRICH	KY	IV	X						X					X							X			X				X		X	X	X		X		X			
BFVICECOS	LA	VI		X						X		X		X			X			X				X	X	X	X	X	X		X	X							
BLACK AND DECKER	NY	II		X					X					X						X				X											X				X	
BLOSENSKI LANDFILL	PA	III	X						X	X	X			X						X				X						X					X					
BOEING OF PORTLAND	OR	X		X					X	X				X							X			X								X	X						
BTL SPECIALTY RESINS CORP.	NY	II		X					X	X				X							X			X							X			X					X
BURLINGTON NORTHERN RR	MN	V			X				X	X				X							X			X			X			X			X					X	X
CAPE FEAR WOOD PRESERVING	NC	IV	X						X					X	X						X			X		X	X				X	X			X				
CAVENHAM CORPORATION	MS	IV		X					X			X		X							X			X						X			X						
CAVENHAM CORPORATION	AL	IV		X					X			X		X							X			X						X			X						
CHEMTRONICS SITE	NC	IV	X						X	X				X							X			X				X							X		X			
CIBA-GEIGY	AL	IV	X	X					X					X							X			X								X							X
COLEMAN-EVANS WOOD PRESERV.	FL	IV	X						X					X							X			X		X														
CONOCO REFINING	OK	VI		X					X	X		X		X				X			X			X		X			X		X	X							
COOPER BIOMEDICAL, INC.	NJ	II			X				X						X						X			X				X				X		X					X
DES MOINES TCE	IA	VII	X						X					X							X			X									X	X					X
DISTLER BRICKYARD	KY	IV	X						X					X				X		X				X	X			X		X		X	X	X					
DISTLER FARM	KY	IV	X						X					X						X				X						X	X	X	X						
DRAKE CHEMICAL	PA	III	X						X					X							X			X	X															
DUPONT-AXIS	AL	IV		X						X				X							X			X							X		X						X
ELECTRONIC CONTROLS, CORP.	MA	I		X					X	X				X							X			X								X	X	X					
ELECTRONIC INDUSTRIES	MN	V				X			X	X				X							X			X							X	X	X						X
EMERSON ELECTRIC	FL	IV				X			X					X							X			X							X		X			X			X
ENSCO	AR	VI		X					X	X				X		X							X	X	X				X		X		X						
EVANITE BATTERY SEPARATOR	OR	X		X		X			X	X		X		X							X			X				X			X		X	X					

Table 2.1
SUMMARY OF GENERAL SITE DATA
(CONT'D)

SITE NAME	STATE	EPA REGION	Administrative Program: Superfund	Administrative Program: RCRA	Administrative Program: State Lead	Administrative Program: DOD / DOE*	Administrative Program: Other	Remedial Objective: Containment	Remedial Objective: W.H. Treatment	Remedial Objective: NAPL Recovery	Remedial Objective: Leachate Coll.	Extraction Type: Wells	Extraction Type: Well Points	Extraction Type: Trenches	System Enhancements: Pulsed Pumping	System Enhancements: Reinjection	Site Type: Underground Storage Tank	Site Type: HAZ. Waste Dump	Site Type: Industrial Plant	Site Type: Ammunition Dump	Site Type: Other	Contaminant Type: Organic	Contaminant Type: Metals	Contaminant Type: High Sorption	Contaminant Type: Low Sorption	NAPLS: Floaters	NAPLS: Sinkers	Aquifer Materials: Clay	Aquifer Materials: Silt	Aquifer Materials: Sand	Aquifer Materials: Gravel	Aquifer Materials: Fractured Rock	Aquifer Materials: Interbedded Sediments	Aquifer Materials: Limestone	Aquifer Materials: Other	Extraction Began
FAIRCHILD SEMICONDUCTOR	CA	IX	X		X			X				X							X			X					X	X	X						X
FERNWOOD WOOD TREATING CO	MS	IV		XX						X																									
FMC CORPORATION	NY	II	X					XX				XX							X			X					X	X	X						XXX
FMC CORPORATION	MN	V			XX																														
FORD MOTOR CO	NJ	II						X																											
FRONTIER HARD CHROME	WA	X	X					X				X							X			X					X	X	X						X
FRUEHAUF CORPORATION	AL	IV		X																															
GEIGER/CAM CIL	SC	IV	X					X				XX							X			X	X		X										
GENERAL ELECTRIC/EAST ST.	MA	I			X					X				X												X									
GENERAL ELECTRIC/PINNELAS	FL	IV				•		XX				XX							X			X	X		X										
GENERAL MILLS	MN	V			X																														
GENRAD CORPORATION	MA	I	X					XX				XX							X			X	X		X										
GILSON ROADS	MA	I	X					XX				XX		X				XX																		
GREAT LAKES CHEMICAL CORP.	AR	VI		X																															
GROVELAND WELLS	MA	I			X				XX																										
HARRIS CORPORATION	FL	IV		XXX				XX				XX							XX			X	X		X										
HELEVA LANDFILL	PA	III	X					XX				XX			X				X			X	X		X										
HOECHST/CELANESE NPL SITE	NC	IV	X					XX				XX							X			X	X		X										
IBM - DAYTON	NJ	II						XX				XX				X			X			X	X		X										
IBM - SAN JOSE	CA	IX	X					XX				XX			X				X			X	X		X										
INDIAN BEND WASH	AZ	IX			X					X						X																			
INTERNATIONAL PAPER CO.	MS	IV				•		XX				XX							X			X	X		X										
KURT MANFACTURING	MN	V			X					X																									
M-AREA SAVANNAH RIVER PLT	SC	IV				•		XX				XX							X			X	X		X										
MEPCO/ELECTRA	NJ	II	X					XX			X	X							X			X	X		X										
MILLCREEK	PA	III		XX										XX																						
MOBAY CORPORATION	TX	VI	X					XXX				XX			X				X			X	X		X										
MOBAY CORPORATION	WV	III		XX																															
NATIONAL STARCH & CHEM.	NC	IV	X					XX				XX			X				X			X	X		X										
NICHOLS ENGINEERING	NJ	II			X																														
NORTHERN TELECOM	FL	IV	X					XX				XX							X		X	X	X		X										
NORTHSIDE LANDFILL	WA	X	X					XX				XX							X			X	X		X										
OLIN CHEMICAL	KY	IV			X																														
OLIN CORP	AL	IV					X	XX				XX							X			X	X		X										
PALMETTO WOOD	SC	IV	X					XX				XX							X			X	X		X										
PENSACOLA NAVAL AIR STA.	FL	IV					X			X																									
PERDIDO	AL	IV	X					X				XX							X			X	X		X										
PERMAPOST PRODUCTS CO.	OR	X		XX				XX				XX							X			X	X		X										

Table 2.1
SUMMARY OF GENERAL SITE DATA
(CONT'D)

SITE NAME	STATE	EPA REGION	Administrative Program: Superfund	RCRA	State Lead	DOD /DOE*	Other	Remedial Objective: Restoration	Containment	W.T. Treatment	NAPL Recovery	Leachate Col.	Extraction Type: Wells	Well Points	Trenches	System Enhancements: Pulsed Pumping	Reinjection	Site Type: Underground Storage Tank	Haz. Waste Dump	Industrial Plant	Ammunition Dump	Other	Contaminant Type: Organic	Metals	High Sorption	Low Sorption	NAPLS: Floaters	Sinkers	Aquifer Materials: Clay	Silt	Sand	Gravel	Fractured Rock	Interbedded Sediments	Limestone	Other	Extraction Begun
PHOENIX-GOODYEAR AIRPORT	AZ	IX	X					X	X				X			X	X			X			X													
PONDERS CORNER	WA	X	X					X		X			X									X	X												X		
REICHOLD CHEMICAL	WA	X		X				X	X				X							X		X	X							X	X						X
REICHOLD PENSACOLA	FL	IV						X	X				X		X					X		X	X	X	X			X	X	X	X		X		X		
ROCKY MOUNTAIN ARSENAL	CO	VIII				X		X	X	X	X		X									X	X	X	X												
ROLLINS-BATON ROUGE	LA	VI		X			X	X	X		X	X	X						X			X	X	X	X	X	X	X	X	X	X		X		X		X
SAPP BATTERY	FL	IV	X					X					X							X								X									
SCRDI/DIXIANA NPL SITE	SC	IV	X					X					X			X				X			X	X				X	X	X			X		X		
SEYMOUR RECYCLING	IN	V	X					X	X				X							X			X		X												
SIDNEY MINE	FL	IV		X				X					X	X	X							X	X	X	X			X	X	X			X		X		
SITE A	FL	IV	X					X	X				X									X	X					X		X							
SODYECO SITE	NC	IV	X	X				X	X				X							X			X			X									X		X
SPARTAN TECHNOLOGY	NM	VI		X				X					X							X			X														
STAUFFER - ICI	AL	IV	X					X					X							X			X					X		X	X						X
TEXAS EASTMAN	TX	VI		X				X	X				X							X			X	X				X		X			X				X
TEXAS ECOLOGISTS	TX	VI		X				X					X							X			X						X	X			X				X
TIME OIL SITE	WA	X			X			X	X			X	X		X				X				X								X						X
TOMAH PRODUCTS	NJ	II	X					X					X			X			X				X					X			X						X
TOWER CHEMICAL	FL	IV	X					X					X							X			X	X	X			X	X				X				
TUSCON INT'L AIRPORT AREA	AZ	IX	X					X	X				X				X			X			X						X								
UN-NAMED	FL	IV					X	X					X							X			X			X											
UNION CARBIDE, PONCE	PR	II		X					X				X							X			X					X									X
UNITED CHROME PRODUCTS	OR	X	X					X					X	X		X				X			X	X			X	X							X		
UPJOHN	PR	II	X	X				X					X							X			X														
UTAH POWER & LIGHT CO.	ID	X																																			
VERONA WELL FIELD	MI	V		X					X				X			X				X			X					X									
VILLE MERCIER, QUEBEC	CN		X					X	X		X		X							X			X				X		X	X				X			
W.R. GRACE	MA	I					X	X	X				X						X				X	X	X	X									X		
WAMCHEM SITE	SC	IV	X					X		X			X							X			X								X	X					
WESTERN PROCESSING	WA	X	X					X	X				X	X			X		X				X	X	X	X		X	X				X				
WHITTAKER SITE	MN	V			X			X	X				X							X			X						X								
WILSON CORNERS (KSC)	FL	IV		X				X					X							X			X					X		X							X
WOOD TREATING, INC.	MS	IV		X				X			X		X							X			X					X		X							
WURTSMITH AFB	MI	V				X		X	X				X					X		X			X		X						X						
WYCKOFF EAGLE HARBOR	WA	X	X					X	X		X		X			X				X			X			X	X	X	X	X							X
ZELLWOOD	FL	IV	X					X					X							X			X	X	X	X	X	X	X	X							

The large number of sites in Region IV should not be interpreted to indicate that Region IV has more ground water contamination problems than other regions. Instead, the high percentage of Region IV sites shows that the individuals familiar with sites in this region were more responsive to the data gathering effort.

2.1.2 Administrative Programs

Five administrative programs are listed by name in Table 2.1, together with an addition column for other programs. Seventy-eight percent of the 112 sites are under the Superfund or RCRA programs. The number of the sites in each program can be broken down as:

EPA Region	Number of Sites	Percent
Superfund	45	40
RCRA	42	38
State lead	24	21
DOD	5	4
DOE	2	2
Other	6	5

Some of the sites are associated with more than one administrative program. The combination of Superfund and RCRA occurred six times and the combination of RCRA and State Lead occurred six times. In some cases, sites may have been transferred from one program to another. In others, a site may have multiple components that are administered by different programs.

2.1.3 Remediation Objectives

The objectives of the ground-water extraction were categorized as: (1) aquifer restoration, (2) plume containment, (3) leachate collection, (4) well-head treatment, and (5) nonaqueous liquid recovery. The number of sites with each objective can be summarized as follows:

Objective	Number of Sites	Percent of 112 Sites
Aquifer restoration	90	80
Plume containment	65	58
Well head treatment	8	7
Nonaqueous liquid recovery	16	14
Leachate collection	3	3

The most common objectives were aquifer restoration and plume containment. Ninety-seven percent of the sites claim either one or the other to be their objective. Forty-one percent (46 sites) have both options as their objective. It is difficult to judge from the general data whether or not aquifer restoration is feasible at each of the sites where it is listed as a goal.

2.1.4 Type of Extraction System

Three extraction system options identified from the general data were drilled wells, well points, and trenches. Ninety-two percent of the sites use drilled wells in their extraction systems. The number of sites in each category is:

Extraction System	Number of Sites	Percent of 112 Sites
Drilled wells	103	92
Well points	5	4
Trenches	9	8
Unknown	3	3

At one of the sites (Sidney Mines) all three extraction types are being employed.

2.1.5 Extraction System Enhancements

Pulsed pumping is employed as a system enhancement at ten sites and reinjection is used at eight sites. Other remedial technologies such as site capping, excavation, vacuum extraction, and bioreclamation, which are sometimes used in conjunction with ground-water extraction systems, were not included in the general data collection effort.

2.1.6 Type of Site

The types of sites encountered in the general data collection effort are categorized as: Underground Storage Tank (UST), Hazardous Waste Dump, Industrial Plant,

Ammunition Dump, and Other. The distribution of the sites in the database for these categories is:

Site Type	Number of Sites	Percent of 112 Sites
UST	1	1
Hazardous waste dump	15	13
Ammunition dump	1	1
Industrial plant	81	72
Other	15	13

2.1.7 Type of Contaminant

Four categories of contaminants were identified in the data collection effort. They were high sorption, low sorption, organics, and metals. In most cases, the individuals providing the data did not indicate whether the contaminants had high or low sorption potential. The number of sites in each category is as follows:

Contaminant Type	Number of Sites	Percent of 112 Sites
High sorption	13	12
Low sorption	26	23
Both high and low	8	7
Organics	106	95
Metals	32	29
Both organics and metals	28	25

2.1.8 Presence of Nonaqueous Liquids

Nonaqueous phase liquids (NAPLs) are present in 46 of the sites in the general survey. Of these 46, 37 sites have NAPLs that are more dense than water and 15 sites have NAPLs that are less dense than water. Six sites have both types of NAPLs.

2.1.9 Geologic Materials

Geologic materials identified in the general data collection program include: clay, silt, sand, gravel, fractured rock, interbedded sediments, and limestone. Most respondents circled multiple materials since most sites are underlain by

several types of geologic materials. The number of sites having materials in each category is:

Geologic Material	Number of Sites	Percent of 112 Sites
Clay	30	27
Silt	46	41
Sand	88	79
Gravel	30	27
Fractured Rock	15	13
Interbedded Sediments	16	14
Limestone	6	5
Other	17	15

2.1.10 Implementation Status

Forty-seven of the sites (42 percent) have pumping in progress. These sites are indicated in the last column of Table 2.1. All other sites are in a pre-implementation phase.

2.2 DETAILED DATA COLLECTION AND CASE STUDIES

Volume 2 of this report consists of case studies for 19 hazardous waste sites at which ground-water extraction systems have been in operation long enough to produce a record of performance. Of these case studies, 18 were developed as part of this project and one, the Ville Mercier study, was taken directly from the technical literature.

The case studies describe the site history, geology, hydrogeology, and waste characteristics to give context to the problem at each site. The remediation system and its performance history is then described, followed by a summary of the case study. Most of the statements concerning site conditions and extraction system performance are derived from information provided by the parties responsible for the sites. However, some conclusions have also been drawn as part of this investigation by the individuals who prepared the case studies. These conclusions are confined to the summary or conclusions sections of the case studies.

Table 2.2 is a summary of the site characteristics at the 19 case study sites. The geographic distribution of case study sites is shown in Figure 2.1. The longest operating record (15 years) is available for the Olin Corporation site, where ground-water extraction was started in 1974. The

Table 2.2
SUMMARY OF CASE STUDY SITE CHARACTERISTICS

Site No.	Site Name	Date of Initial Extraction	Remedial Objective	Chemicals Present	NAPLs Present	Geologic Environment	Innovative Technologies	Administrative Program
1	Amphenol Corporation	January 1987[a]	Restoration[2]	Organics	No	Unconsolidated glacio-fluvial sediments		RCRA
2	Black & Decker	May 1988[a]	Restoration[1]	Organics	No	Glacial till & fractured sandstone	Fracture Enhancement	RCRA
3	Des Moines TCE	December 1987[a]	Restoration[1]	Organics	No	Unconsolidated glacio-fluvial sediments		Superfund
4	Dupont Mobile Plant	December 1985[a]	Containment	Organics	No	Alluvial sand & clay		RCRA
5	Emerson Electric Company	December 1984[b]	Restoration[1]	Organics	No	Sand		State Lead
6	Fairchild Semiconductor	1982[a]	Containment	Organics	Maybe	Alluvial sand & gravel with silt & clay layers	Slurry wall	State Lead
7	General Mills, Inc.	Late 1985[a]	Restoration[2]	Organics	Maybe	Peat, glacial deposits, & fractured rock		State Lead
8	GenRad Corporation	Late 1987[a]	Restoration[1]	Low Sorption Organics	No	Glacial sand, gravel	Intermittent pumping	RCRA
9	Harris Corporation	April 1984[a]	Well-heated treatment & Restoration[1]	Organics Metals	No	Sand & shell with a clay layer	Well points	Superfund & State Lead
10	IBM Dayton	March 1978[a]	Was restoration, now containment	Organics	Yes	Sand with clay layers	Well points Reinjection	State Lead
11	IBM San Jose	May 1982[a]	Restoration[1]	Organics	Yes	Alluvial sand & gravel with silt & clay layers		State Lead
12	Nichols Engineering	January 1988[a]	Restoration[2]	Organics	Maybe	Weathered & fractaured shale		State Lead
13	Olin Corporation	1974[a]	Containment	Organics	No	Unconsolidated glacio-fluvial sediments		State Lead
14	Ponder, Corner	September 1984[a]	Well-head Treatment	Low Sorption Organics	No	Unconsolidated glacio-fluvial sediments	Vapor extraction	Superfund
15	Savannah River Plant	September 1985[a]	Mass reduction	Low Sorption	No	Coastal plain sand, silt & clay layers		DOE
16	Site A	August 1988[a]	Restoration[1]	Organics	No	Limestone & sand		Superfund
17	Utah Power & Light	October 1985[a]	Containment	Organics	Yes	Alluvium & fractured basalt	Intermittent pumping	RCRA

Table 2.2 (Continued)
SUMMARY OF CASE STUDY SITE CHARACTERISTICS

Site No.	Site Name	Date of Initial Extraction	Remedial Objective	Chemicals Present	NAPLs Present	Geologic Environment	Innovative Technologies	Administrative Program
18	Verona Well Field	May 1984[a]	Restoration[1] & Containment	Organics	Yes	Glacial sand, gravel, & clay	Vapor extraction	Superfund
19	Villie Mercier	1983[a]	Containment	High and Low Sorption Organics	Yes	Unconsolidated glacial sediments & fractured rock		Province of Quebec

Notes:

[a] Extraction still in progress.

[b] Remediation completed and extraction system shut down in July 1987.

[1] Restoration to concentration goals equal to or less than health-based standards--MCLs or 10^{-6} excess cancer risk concentrations.

[2] Restoration to site-specific goals not directly related to health-based standards.

Figure 2.1
GEOGRAPHIC DISTRIBUTION OF CASE STUDY

site with the shortest record of operation is Site A, where extraction began at the end of August 1988. Table 2.2 lists the approximate starting dates of the extraction systems described in the case studies. The Emerson Electric site is the only one of the 19 at which the remediation has been completed and extraction has been terminated.

Table 2.2 also shows the administrative program under which the ground-water extraction systems are operated. There are 5 Superfund sites, 5 RCRA sites, 8 state lead sites, 1 DOE site, and 1 site administered by the province of Quebec, Canada. The Harris Corporation site includes three administratively separate parts. All three are administered by the Florida Department of Environmental Regulation, but one is also a Superfund site. Consequently, this site is counted as both Superfund and state lead.

2.2.1 Remediation Objectives

In this study it is important to recognize the differences in remedial objectives for the extraction systems described in the case studies. The remedial goals generally have an important influence on the design and operation of the systems. They must certainly be taken into account when evaluating system effectiveness.

The primary objectives of the ground-water extraction systems at the case study sites are listed in Table 2.2. At 12 of the 19 sites, the current objective includes aquifer restoration. This generally means that the contaminated aquifer is to be remediated to a specified concentration goal. The cleanup standard used is not always a health- or environment-based criterion as defined by current regulations. In some cases, site-specific cleanup goals were established. In others, state requirements that are more stringent than the federal standards have been adopted.

At the Savannah River Plant site, the remediation goal is to remove 99 percent of the estimated mass of subsurface contaminants. This is not a health-based criterion, but it is a quantitative goal for removal of contaminants.

At the IBM site in Dayton, New Jersey, the initial remedial objective was aquifer restoration. However, because it is thought that nonaqueous phase liquids (NAPLs) are present in the aquifer, that goal has been abandoned in favor of plume containment. The design and operating procedures of the extraction system were then modified to increase its containment efficiency. For this reason, both restoration and containment are listed as objectives for this site.

Both restoration and containment are also listed as the objectives for the Verona Well Field site. This was done because the site includes two extraction systems. The objective of one is plume containment, and the other is intended to restore aquifer quality.

Similarly, the Harris Corporation site has multiple extraction systems with different objectives. One is a well-head treatment system, which permits continued operation of water-supply wells in a contaminated aquifer. The other is an aquifer restoration system located near the source of the contamination.

Five of the sites listed in Table 2.2 have been designated as containment systems. This means that aquifer restoration is not expected within the foreseeable future at these sites. This is a somewhat restricted definition of the containment objective, because plume containment is also an objective at most aquifer remediation sites. However, when both restoration and containment are stated objectives of the remediation, aquifer restoration is considered to be the primary objective in this study.

Two of the sites studied--Harris Corporation and Ponders Corner--have well-head treatment systems. These are sites where the primary objective of ground-water extraction is to provide continued water supply from a contaminated aquifer. In both of these cases, the source of the contamination is known, but this is not true at all well-head treatment sites. At the Harris Corp. site the contaminant source is being remediated by a separate ground-water extraction system in addition to the well-head treatment system. At Ponders Corner it is expected that the operation of the production wells with well-head treatment will continue indefinitely. This should eventually result in aquifer restoration. A minimum restoration period of 10 years has been estimated, but no maximum has been projected.

The Verona Well Field is not listed as a well-head treatment site even though it is a producing well field, because the contaminated ground water produced from the blocking wells is not used for water supply. The wells that intercept the contaminant plume are used as blocking wells, which makes this a containment system rather than well-head treatment.

2.2.2 Contaminant Characteristics

Most of the case study sites involved contamination with volatile organic compounds. The most frequently encountered contaminants were chlorinated ethanes and ethenes. The

Dupont Mobile site involved pesticides in addition to chlorinated organics. However, because of their low mobility the pesticides did not figure prominently in the evaluation of extraction system performance. At the IBM San Jose site, Freon 113 was an important contaminant in addition to chlorinated ethenes and ethanes. At the Utah Power and Light site, the only contaminant of concern was creosote, a mixture consisting primarily of phenolics and polycyclic aromatic hydrocarbons. Contamination at the Ville Mercier site included a wide variety of organic compounds and some metals. Both organics and metals were also found at the Harris Corporation site, but the organics were the main contaminants of concern.

The case studies were not intentionally limited to organic contaminants. Several sites were identified where ground-water extraction was being used to remediate aquifers contaminated with metals. However, case studies could not be done for them because of insufficient performance data.

The ground-water remediation programs at several of the sites studied were complicated by the presence of contaminants in nonaqueous phase, as indicated in Table 2.2. At five of the sites, it has been concluded during site investigations that NAPLs are present. This is indicated by a "yes" in the NAPL column of Table 2.2. At three other sites, the presence of NAPLs is suspected by the authors of this report, either because of the high concentrations of dissolved contaminants reported or because of the nature of the contamination source. These sites are designated by a "maybe" in Table 2.2. In many cases no special effort has been made in the site investigations to determine whether NAPLs are present or not.

2.2.3 Geologic Environments

Five of the case studies deal with contamination of fractured rock aquifers. These sites are: Nichols Engineering, Utah Power & Light, General Mills, Black & Decker, and Ville Mercier. Fractured rock aquifers are of special interest because ground-water flow and contaminant transport in them is potentially more difficult to analyze and control. The sites with contamination primarily in unconsolidated sediments include a variety of geologic types, as described in Table 2.2.

At five of the sites, ground water is extracted from more than one aquifer. This generally requires special coordination of the pumping rates in the different groups of wells to properly manage the vertical potentiometric

gradients. These multi-aquifer sites are: Fairchild Semiconductor, IBM Dayton, IBM San Jose, General Mills, and Utah Power & Light.

2.2.4 Use of Innovative Technologies

Few of the sites covered by case studies employed any innovative technologies to enhance the performance of the ground-water extraction systems. All of the sites used drilled wells, but at two sites, well points were also used. Well points are wells that are driven or jetted directly into the ground rather than installed in a drilled hole. Well points are often shallow and are often pumped by surface vacuum pumps.

At the Harris Corporation site, a line of well points was installed to supplement the ground-water extraction from drilled wells. However, the well points developed operational problems and were soon replaced with two conventional drilled wells. At the IBM Dayton site, two lines of well points were installed to supplement the conventional extraction well system. One line of well points was used for ground-water withdrawal, and the other was used for reinjection.

The IBM Dayton site was the only case study where reinjection of treated ground water was employed. In this case, the purpose of reinjection was to influence ground-water flow patterns. The injection wells were operated for only a few months before they had to be abandoned due to clogging of the formation. At the Utah Power & Light site, reinjection was considered as an initial design option, but was rejected because it would interfere with the control of vertical gradients between aquifers.

At the Fairchild Semiconductor site the onsite extraction system was supplemented by an encircling slurry wall to isolate the most heavily contaminated part of the surficial aquifer. The slurry wall has helped the extraction system establish the desired hydraulic gradients between aquifers.

Vapor extraction has been used to accelerate cleanup of contamination above the water table at the Ponders Corner and Verona Well Field sites.

At the Black & Decker site, the density of bedrock fracturing was enhanced by the use of explosives to increase the effectiveness of the extraction wells in capturing contaminants.

Intermittent pumping of the extraction wells has been practiced at the Genrad and Utah Power & Light sites. However, this was not intentionally done to increase extraction efficiency in either case. At Genrad, the extraction has been intermittent to avoid freezing of the above-ground piping during the winter months. At Utah Power & Light, pumping of individual wells has been intermittent because of the limited productivity of the aquifers and frequent shutdowns of the treatment plant. At this site, the relatively high ground-water velocities associated with restarting individual wells may have had a beneficial effect on the recovery of nonaqueous phase liquids, but this has not been clearly demonstrated.

2.2.5 Extraction System Design Information

Table 2.3 presents a summary of information concerning the design of the extraction systems at the 19 case study sites. The first several columns in the table indicate the kinds of site data and the analytical methods that were used in designing the extraction systems. The remaining columns indicate the extraction capacity of the systems, whether the system configuration has been adjusted in response to operating experience, and (where applicable) the expected time required to complete the remediation. This information was taken from the design and operating reports collected for the case study sites during the detailed data collection phase of the study. For some of the sites, the available reports may not have provided complete descriptions of the site data collected or the design methods used.

At all but two of the sites, aquifer testing was done to help determine the hydrogeologic characteristics of the aquifer to be remediated. Aquifer testing, as referred to here, means that a well on the site was pumped at a controlled rate for a certain period of the time, and the resulting water level drawdown was measured in separate observation wells.

Numerical modeling was used to analyze ground-water flow at most of the case study sites. The flow models were generally used to determine capture zones of the planned extraction wells. At six of the sites, the flow patterns predicted by the models were used to estimate the travel times required for contaminants at the edge of the contaminant plume to reach the extraction wells. However, numerical contaminant transport modeling was not used at any of the sites.

Table 2.3
SUMMARY OF DESIGN INFORMATION FOR CASE STUDY SITES

Site No.	Site Name	Aquifer Tests	Flow Model	Travel Time Analysis	Multilevel Sampling	Soil Sampling	Sorption Considered	Pilot Testing	System Modifications	Max. Pumping Rate (gpm)	Projected Cleanup Period
1	Amphenol Corporation	Yes	Yes	Yes	Yes	Yes	Yes	No	No	200	5 to 10 years
2	Black & Decker, Inc.	Yes	No	No	Yes	No	No	No	No	15-20	Not Projected
3	Des Moines TCE	Yes	Yes	Yes	Yes	Yes	Yes	No	No	1300	Not Projected
4	Du Pont Mobile Plant	Yes	No	No	No	Yes	Yes	No	Yes	150-180	N/A*
5	Emerson Electric Co.	No	Yes	Yes	Yes	Yes	Yes	No	No	30	9 Months
6	Fairchild Semiconductor	Yes	No	No	Yes	Yes	No	No	Yes	9,200	N/A*
7	General Mills, Inc.	Yes	Yes	No	Yes	Yes	No	No	No	370	Not Projected
8	GenRad Corporation	Yes	Yes	No	Yes	Yes	Yes	Yes	No	30	> 5 Years
9	Harris Corporation	Yes	Yes	No	Yes	Yes	No	No	Yes	1,000[1] 300[2]	Not Projected
10	IBM Dayton	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	1,000	6-11 Years
11	IBM San Jose	Yes	Yes	No	Yes	Yes	Yes	No	Yes	6,000	10 Years[a]
12	Nichols Engineering	Yes	No	No	Yes	Yes	Yes	Yes	Yes	65	2.25 Years
13	Olin Corporation	Yes	Yes	No	No	Yes	No	No	No	2,600-3,600	N/A*
14	Ponders Corner	Yes	No	No	Yes	Yes	Yes	No	No	1,200	> 10 Years
15	Savannah River Plant	Yes	Yes	Yes	Yes	Yes	Yes	No	No[b]	440	30 Years
16	Site A	No	Yes	Yes	Yes	Yes	No	No	Yes	50	25-60 Days
17	Utah Power & Light	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	200	N/A*
18	Verona Well Field	Yes	Yes	No	Yes	Yes	Yes	No	Yes	2,000[1] 400[2]	Not Projected
19	Ville Mercier[c]	--	--	--	Yes	--	Yes	--	No	750	N/A*

Notes

*Projection of cleanup period is not applicable to containment systems.

[a]Not explicitly projected; figure based on interpretation of design information.

[b]Increase in extraction rates is planned.

[c]Little design information is given in the case study for this site.

[1]Containment or well-head treatment portion.

[2]Restoration portion.

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At all but two of the sites, the subsurface exploration program included multi-level ground-water sampling to determine the vertical distribution of contaminants. This was done at all of the sites involving more than one aquifer and also at many of the single-aquifer sites.

Subsurface soil samples were taken and analyzed at all but one of the case study sites. In most cases, soil sampling was conducted for the purpose of identifying the contaminants present and characterizing the contaminant source. Only rarely were soils sampled over a wider area to study the contaminant sorption characteristics of the aquifer or to search for contaminants in the nonaqueous phase. However, sorption was considered, in one way or another, at all but six of the sites.

Pilot testing, as referred to in Table 2.3, means that a small-scale extraction system was initially installed to provide data for the design of the final system. This was done at four of the case study sites. System modification means that the configuration of the full-scale system was adjusted on the basis of information gathered during performance monitoring. This happened at about half of the sites. In some cases, wells were added or pumping rates were increased because monitoring showed that the initial system was inadequate. In other cases, extraction at some wells was terminated as a result of the progress of the remediation.

The last column of Table 2.3 lists the projected cleanup period as estimated by the designers of the extraction system. At sites where the remedial objective is not aquifer restoration, such a projection is not applicable, and the extraction system is expected to continue operating indefinitely. Even for several of the aquifer restoration sites, no projection of the cleanup time has been made.

2.3 GENERAL CONCLUSIONS

The following general conclusions can be drawn from the case study data collected in this project:

1. The ground-water extraction systems were generally effective in maintaining hydraulic containment of contaminant plumes, thus preventing further migration of contaminants. Even so, the design of successful containment systems requires careful study of site hydrogeology. Hydraulic containment of the contaminant plume was a goal, either primary or secondary, at all

of the 19 case study sites. In most cases, successful containment has been demonstrated.

2. Significant removal of contaminant mass from the subsurface can often be achieved by the operation of ground-water extraction systems. Where site conditions are favorable, and the extraction system is properly designed and operated, it may be possible to remediate the aquifer to health-based levels. However, the time required for complete remediation is usually longer than initially estimated.

3. The contaminant concentrations observed at sites where aquifer restoration systems are in operation typically show a rapid initial decrease and then level off or decrease at a greatly reduced rate. This effect is to be expected because the mass reductions are greatest when contaminants are being removed at high concentration. This effect may also be caused in part by dilution due to the unintentional withdrawal of ground water from regions outside the contaminant plume. Care must be taken to design the aquifer restoration system in a way that maximizes extraction of the most highly contaminated ground water.

4. The success of ground-water extraction systems is highly dependent on site hydrogeology and contaminant characteristics. Site conditions must be taken into account in the selection of realistic system objectives. Even when appropriate objectives have been chosen, the extraction system may be inefficient in achieving them if its design is not based on an adequate site investigation. The data collection practices at some of the sites reviewed did not provide enough information to permit thorough characterization of the subsurface and of contaminant interactions with it.

5. Well-head treatment systems can provide plume containment while maintaining water supply from contaminated aquifers. They are usually installed as a cost-effective remedy for water supply needs. However, at some of the sites studied they were integrated into the overall aquifer remediation as barrier systems to prevent uncontrolled plume migration.

6. It is important to consider the contaminated subsurface, both saturated and unsaturated zones, as an integrated whole, and to design remediation programs to address source areas and unsaturated zone contamination

in addition to the ground-water contamination in the saturated part of the aquifer. Enhanced methods such as pulsed pumping and vapor extraction can potentially improve the effectiveness of ground-water extraction systems by addressing residual contaminant sources in the vadose zone.

2.3.1 Aquifer Restoration

Of the 19 case studies presented in this investigation, only one covers a site where a complete and final aquifer restoration is claimed. This is the Emerson Electric Company site in Altamonte Springs, Florida. The contaminant concentrations in the recovered ground water were reduced from more than 100 ppb for several compounds, and more than 1,000 ppb for one, to less than the detection limits in approximately 2-1/2 years. This cleanup was initially expected to take only 7 months. The progress of the cleanup was measured by taking monthly samples of the ground water from the combined pumping of the five recovery wells. The termination criteria that had been established for the site were met when two successive sampling events showed concentrations below the cleanup levels. The system was then turned off. When two rounds of post-termination sampling from the extraction wells showed concentrations still below cleanup levels, the site was recommended for deletion from the list of state action sites.

Several of the other case studies cover sites where the extraction system appears to be progressing toward eventual aquifer remediation. At Site A, the contaminant concentrations have been reduced below the cleanup goals in most of the monitoring wells. In two monitoring wells the concentrations were still slightly above the goal for benzene after 199 days of extraction, but the trend in these wells appears to be downward also. It was initially projected that the cleanup would take only 60 days.

At the Amphenol site in Sidney, New York, only about two years of performance record are available since the start of extraction. However, the reduction in concentrations observed in the monitoring wells appears to be consistent with the initial prediction that aquifer restoration would be completed in 5 to 10 years.

At the Fairchild Semiconductor site in San Jose, California, aquifer restoration was not an expressed remedial objective, but large offsite areas of three contaminated aquifers have been cleaned up after seven years of extraction. Approximately, 90,000 pounds of chlorinated solvents have been

removed during this time. There are still large areas of offsite contamination, but these appear to be shrinking steadily. Onsite contamination of the uppermost aquifer includes contaminants in nonaqueous phase, which are being contained by a combination of extraction wells and a slurry wall. This onsite containment system will probably need to be operated indefinitely because of the NAPLs.

For the other eight case study sites where aquifer restoration is the objective, the progress that has been made toward this goal varies. At Des Moines TCE, GenRad, and Black & Decker, the data sets are either too short or too sparse to permit a conclusion to be drawn. At Verona Well Field, the existence of a floating layer of nonaqueous phase contaminants makes it unlikely that complete restoration will be achieved in the foreseeable future, even though significant quantities of contaminants are being removed by both the ground water and vapor extraction systems. At the IBM site in San Jose, California, extraction has been continuing for more than 6 years. Large areas of the contaminated aquifers offsite have been cleaned up to MCLs or 10^{-6} excess cancer risk concentrations, but reduction in contaminant concentrations to the more stringent site goals set by the state of California has generally been slow. Onsite contamination has been persistent but some progress is evident. At Nichols Engineering, the available performance record is short, but so far it does not indicate convincing progress. At the General Mills site in Minneapolis, Minnesota, the extraction systems have achieved some initial concentration reductions. However, the apparent existence of a residual contamination source and the possible presence of NAPLs in the aquifers make it doubtful that restoration will be completed soon.

At the IBM site in Dayton, New Jersey, the goal of the aquifer remediation was thought to have been attained in 1984, after 6 years of groundwater extraction. This conclusion was based partly on the reduction of concentrations to low stable levels in most of the off-site wells, and partly on the criteria that had been established for system shutdown. These criteria included the option to terminate the remediation if performance records showed that concentrations were no longer declining. Continued monitoring after extraction had been discontinued showed steady increases in the contaminant concentrations in monitoring wells as the original contaminant plume was re-established. Further study indicated that the re-emergence of the plume may have been caused by the presence of contaminants in nonaqueous phase. Consequently, the objective of the remediation was changed from aquifer restoration to plume containment.

At the Savannah River Plant, the extraction system may not have enough capacity to effectively deal with the magnitude of the contamination problem. Parts of the plume are not presently within the capture zone of the extraction wells. However, an increase in extraction system capacity is planned. Considerable quantities of contaminant have been recovered, but the reduction in contaminant mass in the aquifer appears to be much less than the mass of contaminants recovered. This may be due to recontamination of the aquifer by residual sources including contaminants sorbed to the aquifer materials.

It should be noted that the two case study sites that appear to be in the most advanced stages of aquifer restoration, Emerson Electric and Site A, are not those with the most comprehensive site investigations. The aquifer contamination at both of these sites was thought to be relatively small in scale, although the extent of the contaminant plume has not been fully delineated in either case. This, together with the relative simplicity of the hydrogeologic situation at both sites, has probably contributed to their apparent responsiveness to remediation. However, the data gathered during site characterization and performance monitoring at these sites are too limited to permit this to be stated with unqualified confidence.

2.3.2 Migration Control

At most of the case study sites where the objective is plume containment, the extraction systems seem to have attained this goal. At Fairchild Semiconductor, Verona Well Field, Utah Power & Light, Olin Corporation, and Ville Mercier, the measured potentiometric head distributions indicate that the contaminant plumes are within the capture zones of the wells.

At the Dupont Mobile site, control of contaminant migration may not have been completely established. Potentiometric head measurements at this site appear to show complete hydraulic containment of the contaminant plume. However, contaminant mass balance calculations indicate that only about half of the contamination approaching the extraction wells is being recovered. The discrepancy may be due to inaccuracy in the estimation method used to estimate the mass flux of the contaminant plume. However, it could also arise from incomplete characterization of the ground-water flow patterns around the extraction wells. The ground-water flow has been analyzed two-dimensionally in the horizontal plane, with water levels being measured by shallow partially penetrating wells. The extraction wells are also partially

penetrating, and their capture zone may not extend all the way to the bottom of the contaminant plume. This illustrates the need for adequate vertical hydrogeologic site characterization in the design of ground-water extraction systems.

Incomplete migration control has also been observed at the Savannah River Plant and at the Harris Corporation site in Palm Bay, Florida. At the Savannah River Plant, the extraction capacity is being increased to correct the problem. At the Harris site, the portion of the plume that escapes the on-site wells is captured by the well-head treatment system on the adjoining property, so there is no uncontrolled escape of contaminants.

2.3.3 Well-Head Treatment

In a well-head treatment system, contaminants present in the water extracted by the production wells are removed before the water is put to its intended use. Success in well-head treatment is generally easier to achieve than in aquifer remediation systems because it is not necessary to address the complexities of subsurface contamination. The types and estimated concentrations of contaminants must be estimated in order to design the treatment system, but once this is done, the success of the system depends on the treatment effectiveness rather than on the effectiveness of contaminant recovery. The need to install additional wells is reduced and the monitoring requirements are generally less demanding with well-head treatment systems, making them less expensive to operate. The underlying contamination problem is generally not addressed directly, but some improvements in ground-water quality often occur.

Well-head treatment was used at two sites for which case studies were done--Ponders Corner and Harris Corporation. At Ponders Corner, the well-head treatment system was installed as an interim remedial action intended primarily to restore water supply. However, because the affected production wells are near the center of contamination, the operation of this system has significantly improved aquifer quality compared to initial levels. Well-head treatment can often be an important interim remedial measure that allows the beneficial use of ground water to continue during the formulation of a final response. In cases where aquifer restoration is not practicable, well-head treatment can still be a realistic alternative that allows the beneficial use of ground water to continue.

At the Harris Corporation site, the water purveyor affected by contamination from the Harris Corporation facilities has installed a well-head treatment system to maintain its water supply. This treatment system is part of a complex containment and aquifer restoration effort in operation at the Harris facilities. This is a case in which well-head treatment is part of a phased approach that permits beneficial use of the aquifer in the short term while a long-term solution to its restoration is being attempted.

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Chapter 3
FACTORS AFFECTING SYSTEM DESIGN AND PERFORMANCE

Ground-water extraction technology is based on two fundamental assumptions. First, it is assumed that a well system can produce ground-water flow patterns that will permit the wells to withdraw all of the contaminated ground water from the aquifer. Second, it is assumed that the contaminants will come out of the aquifer with the water. In an ideal hydrogeologic system with simple pre-existing flow patterns, homogeneous aquifer properties, and with mobile contaminants present only in aqueous solution, ground-water extraction can work quite well. However, most real-world sites are more complex than this, and most departures from the ideal conditions described above tend to reduce the potential effectiveness of ground-water extraction. This chapter will discuss the effects of some of these departures from ideal conditions on the design and performance of extraction systems.

Again, it is necessary to distinguish the different objectives of ground-water extraction systems. For migration control systems it is only necessary to establish a hydrodynamic regime that will ensure capture of the contaminated ground water. The time required for contaminant removal is not an issue. For aquifer remediation systems, control must be established over the movement of both the ground water and the contaminants. Because migration control systems have fewer requirements, they will be considered first.

3.1 FACTORS AFFECTING MIGRATION CONTROL

The design of successful migration control systems depends on the ability to predict the ground-water flow patterns that will be produced when the effects of the extraction wells are added to the pre-existing flow system. Before such predictions can be made, an understanding of the hydrogeologic properties of the site and the spatial distribution of the contamination must be acquired. Chapter 4 discusses the information requirements for system design.

3.1.1 Contaminant Distribution

The proper definition of the vertical and horizontal limits of contamination is essential in designing almost all remediation systems. The failure to define the limits of

the plume can lead to incorrect recovery well placement and pumping rates.

3.1.2 Effects of Pre-Existing Gradients

The potentiometric head distribution that exists in the aquifer before the extraction well system is added is referred to as the field of pre-existing gradients. This is not necessarily the natural flow field, because the flow may be affected by nearby ground-water withdrawals.

At sites where the pre-existing gradients are uniform and unidirectional, the analysis of migration control wells is relatively simple. A well-known technical article by Javandel and Tsang (1986) provides a graphical method based on potential flow theory for the design of single-well or multiple-well plume containment systems in such cases. An equivalent analysis can be performed by any trained hydrogeologist simply by superimposing the drawdown predicted for the extraction wells onto the uniform gradient field. Strictly speaking, this method applies only to flow in confined aquifers, but the error involved in applying it to unconfined situations is generally small.

When the pre-existing flow field is nonuniform, the analysis of the effects of extraction wells is likely to be more complicated. If the nonuniformity of the flow is caused by the presence of nearby production wells, as is often the case near well fields, the superposition principle still holds. The superposition procedure will then be somewhat more cumbersome than in the case of a uniform regional gradient, but it is still not particularly difficult. However, the observation that the pre-existing flow field is complex is often an indication of significant heterogeneity in aquifer properties. This is considerably more difficult to deal with, as discussed below.

Case study sites where the flow induced by nearby production wells may not have been adequately accounted for include the Dupont Mobile site and the Harris Corporation site.

In the above discussion of gradient fields, the problem has been implicitly interpreted as being two-dimensional in the horizontal plane. This is one of the common idealizations used to simplify reality for ease of analysis. However, if there are significant vertical gradients in the aquifer to be remediated, a two-dimensional representation is not adequate. Significant downward flow in an aquifer can indicate that it is discharging to a lower hydrologic unit. The extraction well system must then be capable of reversing

the flow between aquifers in the contaminated area as well as effecting plume capture with respect to horizontal flow. Case study sites where flow between aquifers was of concern include Savannah River Plant A/M-area, General Mills, Fairchild Semiconductor, IBM San Jose, IBM Dayton, and Utah Power & Light. Vertical flow may have been important at Site A also, but it was not taken into account in the design of the extraction well.

3.1.3 Effects of Aquifer Properties

3.1.3.1 Transmissivity

The aquifer's response to ground-water withdrawals from the extraction wells is determined primarily by its hydraulic conductivity and saturated thickness. The product of these two properties is the aquifer transmissivity.

In a low-transmissivity aquifer, the radius of influence of an extraction well will be smaller than it would be in a high-transmissivity aquifer. This is illustrated schematically in Figure 3.1. Consequently, in an aquifer with low transmissivity, more extraction wells must be used and they must be more closely spaced if an effective hydraulic barrier is to be formed. The spacing problem may be further aggravated in unconfined aquifers, where the aquifer's saturated thickness may limit the maximum drawdown of individual wells. In aquifers with such restrictive conditions, extraction trenches or lines of closely spaced well points are sometimes used instead of drilled extraction wells. Among the case study sites there were none that used extraction trenches. However, as Table 2.4 shows, several of the sites identified in the general data survey employ trenches for ground-water extraction. Lines of well points were used at IBM Dayton and at the Harris Corp. site, even though the transmissivities of the aquifers there were not particularly low.

3.1.3.2 Heterogeneity

A migration control system that would be effective in a homogeneous aquifer may fail to completely capture the contamination in an aquifer that has nonuniform hydrogeologic properties. Heterogeneity can cause shifts in the cones-of-depression around individual wells that may allow contaminants to flow between or around them. Vertical differences in hydraulic conductivity at an extraction well can cause its radius of influence to vary with depth. This could provide gaps for the escape of contaminants between extraction wells.

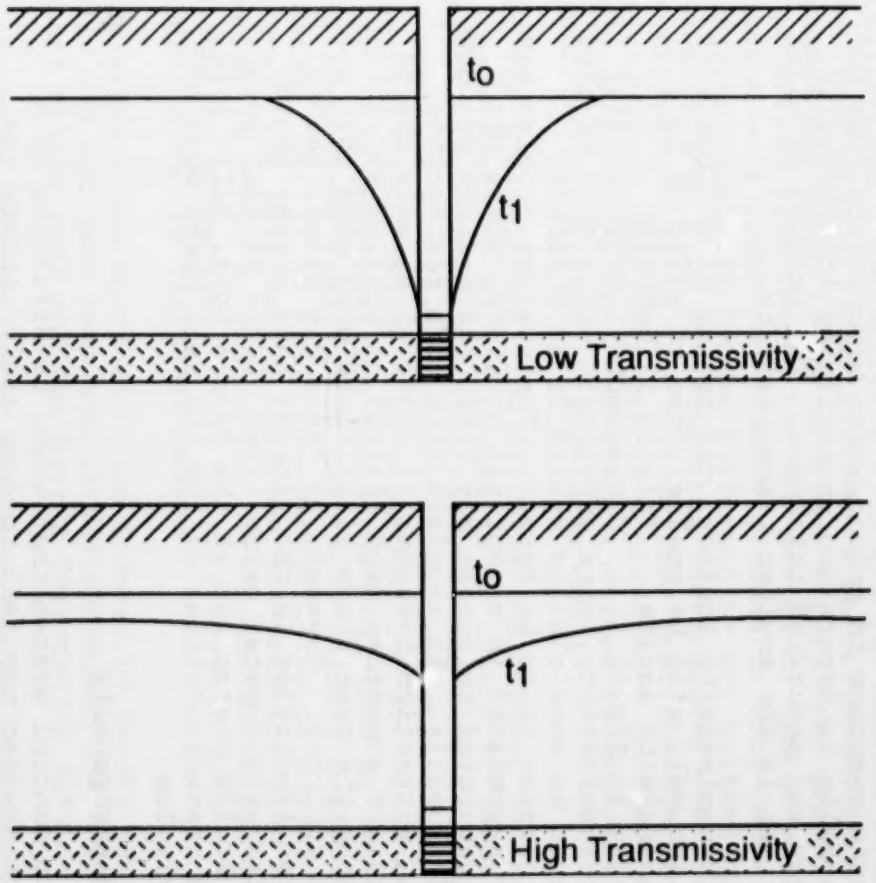

Figure 3.1
COMPARISON OF THE CONE OF DEPRESSION IN LOW CONDUCTIVITY AND HIGH CONDUCTIVITY AQUIFERS

The Amphenol case study provides an example of a site where aquifer heterogeneity led to differing patterns of flow over the depth of a single aquifer. Vertical variations in aquifer flow and contaminant distribution were studied by monitoring multi-level wells. The resulting extraction system included separate recovery wells for the shallow and deep portions of the aquifer.

Problems associated with aquifer heterogeneity are potentially most severe in fractured-rock or karst aquifers. In these cases, the aquifer may not behave as a porous medium, but may be more properly represented as a network of more-or-less interconnected conduits. In such complex systems, the design of aquifer remedial measures may be reduced to trial and error. At the Utah Power & Light site, for instance, some of the extraction wells that were installed failed to produce water at high enough rates to be useful. Other wells had to be installed to replace them, and to a certain extent, the system operators have to live with whatever production they can get from a well. It can also be questioned at this site whether the potentiometric head maps prepared on the basis of observed water-level measurements provide an accurate description of the actual ground-water flow patterns. In the absence of any other technique, head maps are being relied on to verify that the desired capture zones are being maintained.

Nonuniform distributions of aquifer properties make the design of effective migration control systems much more complicated. In these situations, the flow patterns that will be generated by extraction wells are usually predicted with the help of numerical models of ground-water flow. Many computer programs are available for this purpose, and some of them are quite elaborate. However, to get reliable predictions using the models, a very thorough site investigation may be required to get an adequate understanding of the spatial distribution of aquifer properties. Even after intensive investigation there will always be a certain degree of uncertainty about the correct numerical representation of the aquifer. Calibration and verification of the model against site data and testing of the model's sensitivity to changes in parameters should be used to determine appropriate factors of safety in the design of the migration control system.

3.2 FACTORS AFFECTING AQUIFER RESTORATION

When the remedial goal is aquifer restoration, the time required to clean up the contaminated aquifer becomes an

important consideration. To achieve timely aquifer restoration, the ground-water extraction system must not only produce the desired flow directions but must also generate the highest practical flow velocities throughout the contaminated region. These hydrodynamic objectives are generally necessary, but not sufficient, to assure the success of the aquifer restoration.

In many cases, depending on the contaminant and aquifer characteristics, the movement of large quantities of ground water may not produce corresponding reductions of contaminant concentrations. This can happen for several reasons. The ground-water flow generated by the extraction system may not penetrate into low-permeability zones in the aquifer, the contaminants may be strongly sorbed to the aquifer materials and therefore move at a lower velocity than the ground water, or there may be residual sources that replace the contaminants as they are removed from the aquifer.

3.2.1 Well Placement and Pumping Rate

Because of the concern for timely performance in aquifer restoration, the configuration of the extraction well systems are likely to be different than they would be for plume containment systems. For efficient contaminant removal, it is necessary to minimize the time required for contaminants to travel to the recovery wells.

One approach to this is to install a large number of recovery wells distributed throughout the contaminant plume. In low-transmissivity aquifers this may be necessary because of the small radius of influence of the individual wells. However, interference between wells in such a system causes areas of low hydraulic gradient, known as stagnation regions. In these stagnation regions there is practically no ground-water flow, and contaminant removal may be very slow. In some cases this problem can be overcome by alternating the operation of adjacent wells. A more common approach, however, is to progressively reduce the number of operating wells by turning off peripheral wells as the size of the contaminant plume is reduced. This method has been used at the Fairchild Semiconductor and IBM-Dayton case study sites.

In relatively transmissive aquifers, it may be more efficient to concentrate the recovery effort near the center of the contaminant plume. In this way the stagnation regions generated can be reduced to small areas between adjacent wells rather than broad areas between widely spaced

wells. As much as possible, multiple recovery wells should reinforce each other rather than draw ground water in conflicting directions. The costs of piping the extracted ground water to a central treatment plant can also be reduced in this way. This was the approach used at the Des Moines TCE site. Here, the aquifer was transmissive enough that a cluster of 6 extraction wells located near the contamination source could produce a capture zone encompassing the entire contaminant plume.

The selection of well placement and pumping rates are related. The zone of capture of a well network can be increased both by increasing individual well capacity and by increasing the number of recovery wells. The usefulness of increasing pumping is limited in cases where drawdowns become too great for efficient operation of the wells. In these cases, greater numbers of recovery wells are needed. Operational pumping rates can also be limited by the size of the well casing and pump installed at each well location and by interference between wells.

3.2.2 Contaminant Sorption and Retardation

Many contaminants tend to adsorb to and be retained by the solid materials of the aquifer. The effect of sorption to the stationary aquifer materials is to retard the rate of contaminant migration and defeat the efforts of the aquifer restoration system. The relative tendency for contaminants to be retarded by adsorption depends on the chemical properties of both the contaminants and the aquifer materials. Contaminants that are highly soluble adsorb less and are more mobile. Contaminants with low aqueous solubility are more highly sorbed and less mobile. Soils with high organic carbon content or high percentages of clay mineral are more adsorbent and tend to retain contaminants longer. The solubility, density and mobility of common contaminants are shown in Appendix A.

The effect of contaminant sorption on aquifer restoration systems can be considered in a couple of different ways. In the analysis of solute transport in porous media, it is customary to account for adsorption through a retardation factor. (See Appendix B for the definition of the retardation factor.) Using this concept, the migration velocity of the adsorbing contaminant can be deduced by dividing the interstitial ground-water flow velocity by the retardation factor. Thus, if the time required for water particles to travel from the hydraulically most remote edge of the contaminant plume to the extraction wells can be predicted, the aquifer cleanup time can also be estimated by

multiplying by the retardation factor. Of course, this estimate will be based only on advective contaminant transport, neglecting hydrodynamic dispersion.

The advantage of this simplified estimation procedure is that it requires only a hydrodynamic analysis of the flow field generated by the extraction system. If the effects of dispersion are to be included in the estimate, solute transport modeling is required. This usually means that a numerical model must be employed, because closed-form solutions for solute transport are available for only the simplest flow configurations. None of the detailed site data collected in this investigation indicated that solute transport modeling had been used to predict the remediation time at any of the case study sites.

A second way of considering the effects of contaminant adsorption is based on the concept of pore volume sweeping. In this method, it is recognized that sorption results in the partitioning of contaminants between the solid and aqueous phases. This means that at any given time a certain percentage of the contaminant mass is dissolved in the flowing ground water, and the rest is adsorbed to the stationary aquifer materials. If linear equilibrium sorption is assumed, it can be shown (see Appendix B) that the fraction of the total contaminant mass that is in aqueous solution is the reciprocal of the retardation factor. The restoration of the contaminated aquifer can then be viewed as a process of sweeping fresh ground water through the contaminant plume, allowing it to desorb contaminants from the aquifer materials, and removing the contaminated ground water through the extraction wells. This concept was obviously adopted by several of the designers of the aquifer remediation systems in the case studies, because the expected progress of the remediation was often expressed in terms of numbers of pore volumes removed.

The use of the pore volume sweeping concept leads to the expectation that the contaminant concentrations produced from the recovery wells will decline exponentially with time. Experience drawn from the restoration case studies indicates that the concentrations typically do tend to decline rapidly at first, and more slowly later. However, the data are usually too irregular to conclude that an exponential representation is accurate.

It has often been asserted that the linear equilibrium sorption model is an over-simplification of the sorption-desorption process and that kinetic constraints cause the

desorption of contaminants to lag behind the rate at which ground-water flow can remove contaminants from the aquifer. The result of this phenomenon would be that residual contamination remaining in the aquifer after the cleanup was thought to be complete would cause ground-water contaminant concentrations to rise again after the restoration system was shut off. This has not been observed at any of the case study sites in this investigation. System operation has been terminated at only two of the case study sites: Emerson Electric and IBM Dayton. At Emerson Electric limited post-termination monitoring has given no indication of a rise in concentrations. At IBM Dayton, post-termination monitoring did indicate the re-emergence of the contaminant plume, but this has been attributed to the presence of contaminants in a residual nonaqueous phase (NAPLs).

3.2.3 Isolation of Low Permeability Zones

Another factor that can impede the progress of aquifer restoration systems is the presence of trapped contaminants in low-permeability layers or lenses within the aquifer. Ground-water extraction will cause preferential flow in the high-permeability zones, bypassing the silt and clay lenses. Contaminants in the low-permeability zones will then remain as residual sources after the rest of the aquifer has been cleaned up. This problem is thought to be impeding the progress of the remediation at the Ponders Corner case study site.

3.2.4 Contaminants in Nonaqueous Form (NAPLs)

Aquifer restoration at sites where residual contamination is present in nonaqueous form is likely to be very slow. The reason for this is that the mass of contamination contained in the NAPLs is generally very large compared to the mass that can be carried away in aqueous solution. Consequently, a long time must pass before the flowing ground water can exhaust the supply of contaminants contained in even a relatively thin NAPL layer.

If the nonaqueous liquids are less dense than water and tend to float on the water table, it may be possible to accelerate the removal process by recovering some of the contaminants as nonaqueous liquids. This is often done at fuel spill sites. However, as the removal progresses, the NAPL saturation of the soil will be reduced and the NAPLs will cease to flow readily to recovery wells. This results in an almost immobile NAPL-contaminated zone that still contains large amounts of contamination. Auxiliary

restoration techniques such as vapor extraction or bio-remediation can sometimes be used to further accelerate the removal of the floating NAPLs. At the Verona Well Field case study site, vapor extraction is being used in conjunction with ground-water extraction to deal with a floating NAPL layer.

If the NAPLS are more dense than water, they can be expected to sink through the aquifer, leaving a path of NAPLs at near-residual saturation in their wake. If there is a sufficient volume of the NAPLs, they may reach the bottom of the aquifer and flow along its surface. In such cases, it may be difficult to locate all of the NAPL pools, and the technical means for removing them are limited. Several of the case study sites are believed to have residual sources of dense NAPLs. In each of these cases it has been concluded that aquifer restoration is not feasible.

3.2.5 Leaching of Contaminants from the Vadose Zone

Contaminants adsorbed to the soils above the water table represent a source of continuing aquifer contamination that can significantly lengthen the time required for aquifer restoration. Several approaches have been used in the case studies to deal with vadose zone contamination.

At the Amphenol site, soil aeration was used as part of the lagoon closure program before ground-water extraction was started. The mass of volatile contaminants was thus reduced to an allowable residual concentration that would not cause leaching into the saturated part of the aquifer to interfere with the aquifer restoration.

At the Ponders Corner site a vapor extraction system was installed to reduce the contaminant content of the vadose zone soils.

At the Utah Power & Light site the contaminant source area was capped to reduce the rate of infiltration through the contaminated vadose zone.

Chapter 4
INFORMATION REQUIREMENTS FOR SYSTEM DESIGN AND OPERATION

The degree of site characterization necessary to design an effective ground-water extraction system depends on the objectives of the remediation. In cases where well-head treatment is the objective, it may be sufficient simply to characterize contamination to the extent necessary to design the treatment system. The site characterization requirements for an aquifer restoration system are likely to be far more extensive. Before designing an aquifer restoration program, it is generally necessary to characterize: 1) the hydrogeologic properties of the geologic layers involved, 2) the types and distributions of contaminants, 3) the location of sources and their potential for continued contamination of the saturated zone, and 4) the contaminant migration properties of the contamination in the affected aquifers. In addition, successful operation of the system requires that the actual performance of the implemented design be monitored so that adjustments can be made to optimize performance.

4.1 HYDROGEOLOGIC INFORMATION

Whatever the remedial objective of the ground-water extraction system, its functional purpose is to establish some form of control over ground-water flow in the vicinity of the wells. To design a system of wells that can establish this control requires an adequate understanding of the hydrogeologic characteristics of the site. For the design of an extraction system, the necessary hydrogeologic information includes the stratigraphy, the hydraulic conductivity of aquifer layers, the leakance of semi-confining layers, and the natural distribution of potentiometric head.

4.1.1 Stratigraphy

It is necessary to identify the number and thickness of the aquifers potentially affected by contamination at the site. It is also important to know the lateral extent and continuity of any confining or semi-confining layers. Any local gaps in the confining layers that occur within the area of concern can have an important effect on the success of the aquifer remediation. This is illustrated at the IBM Dayton site, where local holes in the clay layer between the upper and lower aquifers are blamed for permitting DNAPLs to enter the lower aquifer.

It is also very important to establish the bottom of the zone involved in the remediation. This is illustrated at the Dupont Mobile site, where offsite flow of contaminants in the lower portion of the aquifer is suspected as the failure mechanism of the migration control system.

Adequate investigation of site stratigraphy requires installation and appropriate logging of enough exploratory borings to characterize the site. The number of borings required depends on the complexity of the subsurface configuration.

4.1.2 Aquifer Hydraulic Properties

In relatively homogeneous aquifers the main reason for investigating the transmissivity is to predict the extent of the capture zone that can be established by wells and the rate of pumping that will be required. The most reliable way of determining this is by conducting an aquifer test. Aquifer test results were used in the design of the extraction systems at most of the sites covered in the case studies. The exceptions to this are Site A, and the Emerson Electric site. At Site A, the design was apparently based on regional hydrogeologic information. At Emerson Electric, the design was based on slug testing.

When the stratigraphy is well defined and good transmissivity estimates can be made, the depth-averaged hydraulic conductivity can easily be determined. Good hydraulic conductivity estimates are necessary if the velocity of the contaminant migration induced by the extraction wells is to be estimated. However, the depth-averaged hydraulic conductivity estimates arising from aquifer test results may be deceptive if the aquifer is vertically heterogeneous. Determination of vertical hydraulic conductivity variations within an aquifer unit requires special testing methods. In open hole wells this can be done by packer testing or spinner logging. In unconsolidated materials, individual slug tests on wells screened at different depths or comparative of grain size analyses can be used to estimate vertical permeability variations.

At the Nichols Engineering site multiple aquifer tests were run at different depths in the fractured bedrock to develop a conceptual understanding of vertical variations in permeability.

In aquifers with complex heterogeneity, conventional aquifer tests can be difficult to interpret. A more useful approach

then is to run a long-term aquifer test in which a large number of observation wells is monitored. An example of this is the aquifer test done at the Amphenol site, where all of the site monitoring wells were used to observe the effects of a 3-day pumping test. The resulting flow patterns were then used to guide the design of the ground-water extraction system.

Another useful way of dealing with complex hydrogeologic systems is pilot testing of extraction wells. This usually involves incremental design of the extraction system as successive components are installed and tested. This approach was used at most of the larger case study sites.

The determination of aquifer storage coefficients is of secondary importance at most sites because the operation of the extraction system is usually analyzed as a steady-state phenomenon. Normally, the time required for significant contaminant migration to occur is much longer than the transient response period of the aquifer.

In multi-layered hydrogeologic systems, the thickness and hydraulic conductivity of the semi-confining layers separating individual aquifers can have an important influence on the effectiveness of ground-water extraction systems. Inter-aquifer leakage in response to the pumping of extraction wells can drastically reduce the radius of influence of the wells. This may be what is happening at Site A, where pumpage of the extraction well has not produced a noticeable drawdown in any of the monitoring wells.

Leakage through semi-confining layers also permits contaminants to move between aquifers. This was a major consideration at the General Mills and Utah Power & Light sites, where the extraction systems in each aquifer were designed to reverse natural downward flow in the areas of high contamination.

4.1.3 Potentiometric Gradients

It must be recognized that ground-water extraction systems achieve their remedial goals through the manipulation of ground-water flow patterns in the contaminated aquifers. At most sites, the potentiometric gradients produced by the extraction wells must compete with a larger scale regional gradient that is attempting to move the contaminants in an undesired direction. These regional gradients may arise naturally, or they may be the result of nearby production wells that are to be protected from contamination. In any

case, the design of the extraction system must take them into account. This requires the installation and monitoring of a sufficient number of piezometers or water level monitoring wells. Since natural gradients can change seasonally, the water levels in the wells must be measured enough times to determine the range of gradients that may occur. The Amphenol and Utah Power & Light case studies illustrate the importance of seasonal variations in potentiometric head.

At most of the case study sites the pre-existing gradients were taken into account in the design of the extraction systems. At Site A, the horizontal gradients were said to be small and were effectively neglected in the design of the extraction system. Vertical gradients at Site A were apparently neglected also.

4.2 CONTAMINANT DISTRIBUTION AND CHARACTERISTICS

Before an effective remedial response can be designed, it is necessary to evaluate the nature of the ground-water contamination problem. This involves determination of the number and identity of the contaminant compounds present, their concentration and spatial distribution in the aquifer, and their mobility characteristics.

4.2.1 Identification of Contaminants

This is probably the aspect of the site investigation that is routinely most thoroughly covered. It is important in the design of an extraction system because of the different mobility and toxicity of the various contaminants and because of the special handling and treatment problems associated with some compounds.

At most of the sites presented in the case studies, the contaminants of concern were volatile organics. These compounds have relatively high mobility as dissolved species in ground water. They are also relatively easy to treat using air stripping or carbon adsorption.

When a variety of compounds with different characteristics is present, the design of the recovery system may become more complicated due to the different mobilities involved. At the Ville Mercier site the ground water was contaminated with a large number of different compounds. Since the extraction system objective was migration control, the wide range of mobilities had no effect on the placement of the wells. However, if the intent were to remediate the aquifer

expeditiously, multiple extraction systems might be required to address individual groups of compounds that had travelled different distances from the source.

In addition to the chemical identity of the compounds, it is also important to determine whether they are present in a nonaqueous phase. If NAPL contamination is involved, it is unlikely that aquifer restoration by an extraction system will be successful. At several of the case study sites, NAPL contamination was known to be present. At the IBM Dayton, Utah Power & Light, and Ville Mercier sites, the remedial objective was limited to migration control because of them. At the IBM San Jose site slurry wall containment was used to isolate the NAPL-contaminated region, and at Verona Well Field a vapor extraction system was installed to deal with it.

At several of the other sites, no special site investigation was conducted to determine the presence of NAPL contamination, even though the mode of waste disposal or the high concentrations in the ground water might have suggested it. Because of interfacial tension effects, NAPLs that are present in an aquifer at relatively low saturation may not flow into a well. Therefore, the presence of NAPLs cannot be ruled out just because they have not been seen as a separate phase in any of the ground-water samples. A more reliable way to detect nonaqueous phase contamination is to take soil samples during installation of the monitoring wells (e.g. split-spoon or Shelby Tube samples) or as part of a separate soil boring program. In fractured rock aquifers, rock coring can be used to collect aquifer samples but this may not conclusively rule out NAPL presence.

4.2.2 Contaminant Distribution and Concentration

Knowledge of the spatial distribution of contaminants in the aquifer is obviously very important in the design of an extraction system because it determines the area in which control of ground-water flow must be established. The problem is, essentially, to determine the boundaries of the contaminant plume. This generally requires monitoring wells to be installed both inside and outside the contaminated area. If all of the wells are inside the contaminated area, its edge cannot be located.

In the design of plume containment and well-head treatment systems it may not be essential to establish the upgradient extent of the contaminant plume. But, the downgradient and lateral extent of the area in which health-based standards are exceeded must be known.

Accurate measurement of contaminant concentrations is important for several reasons. First, the aquifer restoration goals are expressed in terms of individual contaminant concentrations, so the boundaries of the contaminated region are determined by the concentrations of the contaminants. Second, predictions of the contaminant concentrations in the extracted ground-water are required in the design of the treatment system. Third, the best way to measure the progress of aquifer remediation is by periodic comparison of the contaminant concentration distribution with the initial distribution that existed before the remediation began.

Concentration distributions are usually described by drawing contour maps of the contaminant plume. In most of the case studies, contaminant contour maps are presented for the initial site conditions and for subsequent times during the remediation period. This greatly facilitates the evaluation of remedial effectiveness. However, no concentration contour maps were available for the Emerson Electric, Site A, and Utah Power & Light studies.

When interpreting the meaning of concentration contour maps it is important to understand how vertical variations in contaminant concentration have been accounted for. In many cases, the possibility of vertical concentration gradients is neglected. The contour maps may be developed directly from the analytical results without regard to the depth from which the samples were taken or the length of the screened intervals in the monitoring wells. This can give a false impression of the distribution of contaminants in the aquifer. If the samples were taken from fully penetrating monitoring wells, the results can be interpreted as a permeability-weighted depth-averaged concentration. Such a concentration measurement is useful in predicting the contaminant concentrations that will be produced by fully penetrating extraction wells. However, concentrations measured in this way will probably be lower than the maximum concentrations in the aquifer and may produce incorrect estimates of total contaminant mass.

Estimates of the total contaminant mass in the aquifer are sometimes used as an expression of the magnitude of the problem to be remediated. At the Savannah River Plant, the goal of the aquifer restoration system was to remove 99% of the contaminant mass in the aquifer in 30 years. Evaluation of the performance of this system therefore depends heavily on the accurate estimation of this contaminant mass. This requires an understanding of the three-dimensional distribution of contaminant concentration in the aquifer,

which can only be obtained by multi-level sampling. Both dissolved and sorbed contaminants must be accounted for in estimates of the total contaminant mass (see Appendix B).

4.2.3 Contaminant Mobility Characteristics

One of the most common explanations for the underestimation of the time required for aquifer remediation is that the effects of adsorptive retardation were not accounted for. This may have been the case at Site A and at the General Mills site. Adsorptive effects may also have been underestimated at the Savannah River Plant. At most of the other sites studied, the retarding effects of contaminant sorption were acknowledged by estimating that multiple pore volumes would have to be extracted before the concentrations could be reduced to the regulatory standards.

Quantitative estimates of contaminant retardation are usually based on the total organic carbon content of the aquifer materials and tabulated values of partition coefficients for organic compounds. At most of the case study sites, however, no measurements of total organic carbon in the soils were made.

At the Amphenol site, soil samples were taken from beneath the contaminant source area and subjected to laboratory testing to evaluate the partitioning of contaminants between soil and water. This was done to support analysis of the continued leaching of contaminants from the contaminated vadose zone into the underlying aquifer. Laboratory testing of site materials to determine partition coefficients is fairly rare at ground-water contamination sites, but the information obtained from such tests is quite useful.

4.2.4 Identification of Contaminant Sources

Adequate characterization of the sources of contamination is important in the design of most aquifer remediation systems. This is particularly true of systems designed for aquifer restoration, where the existence of continued contaminant input from residual sources can defeat the ground-water cleanup efforts.

Usually, the original source of the contamination is known, although this was not the case at the Site A and Emerson Electric sites. But, when the original source has been removed, it is important to evaluate the potential for continued leaching of contaminants from the remaining contaminated soils. It may be advisable to consider

additional soil removal or surface capping to reduce infiltration of contaminants to the ground water.

4.3 PERFORMANCE MONITORING REQUIREMENTS

The performance of the ground-water extraction system must be monitored regularly to ensure that the desired control is being maintained over the ground-water flow patterns and the movement of contaminants.

Monitoring of the hydraulic performance of the system is done by regular measurement of water levels in piezometers and monitoring wells throughout the area of remediation. Potentiometric surface maps are then drawn for each of the aquifers of concern to show that the desired capture zones are being maintained. In multi-aquifer situations the potentiometric gradients between aquifers are also checked using these maps.

Monitoring of the aquifer cleanup effectiveness of the extraction system can be done in several ways. One way that is rather common, but not very reliable, is to monitor the flow rate and contaminant concentrations produced by the extraction wells. Integration of the product of flow and concentration over time gives an estimate of the mass of contaminants removed. This is an interesting statistic, but it does not provide a direct measure of the reduction in contaminant concentrations in the aquifer.

The measurement of contaminant concentrations should not be limited to samples taken from the production wells. Samples should also be taken simultaneously from enough monitoring wells in the remediation area to permit plume maps to be drawn. It is such plume maps that should ultimately be used to determine when the aquifer remediation is complete. Samples taken from the extraction wells are not reliable for this because of the considerable dilution that these wells generally produce through their hydraulic effects on the aquifer.

In monitoring plume containment systems, it is important that some monitoring wells be located downgradient of the extraction wells. This is necessary so that flow reversal downgradient of the well can be demonstrated. Hydraulic measurements are usually relied on as the primary indicator of success in plume containment systems. However, periodic water quality sampling should be performed also to ensure that contaminants are not escaping by passing under or between the wells. As illustrated by the Dupont Mobile

site, the appearance of complete hydraulic capture on the basis of potentiometric heads can be deceptive if the hydrogeologic nature of the aquifer is not well understood.

4.4 POST-TERMINATION MONITORING

Performance monitoring at the aquifer restoration sites should continue even after the extraction system ceases to operate. It is to be expected that the low contaminant concentrations measured toward the end of the remedial action may rebound after the extraction system has been turned off. This can happen for a variety of reasons. One possibility is that the ground-water flow patterns generated by the extraction system can cause dilution of the concentrations sampled at monitoring wells. Another possibility is that residual contaminants stored in low permeability zones of the aquifer sorbed to the aquifer materials, or retained as NAPLs, may cause the concentrations to rise when the extraction is terminated. Also, the recovery of water levels after system shutdown may resaturate contaminated soils.

This phenomenon has been observed in only one of the case studies, at the IBM Dayton site. At Emerson Electric, two rounds of post-termination sampling from the extraction wells have not indicated any resurgence of contamination. None of the other sites have progressed far enough for the extraction systems to be shut down.

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Chapter 5
METHODS OF INCREASING SYSTEM EFFECTIVENESS

Several enhancement techniques have been proposed as ways to improve the performance of ground-water extraction systems, either by accelerating the aquifer remediation or making it more efficient. At most of the case study sites in this investigation, conventional ground-water extraction, consisting of continuous pumping from a fixed number of recovery wells was the only technology employed. However, at a few of the sites attempts were made to increase the effectiveness of the basic system. The enhancement techniques used included: progressive modification of the extraction well configuration, pulsed pumping, auxiliary physical containment, reinjection, vapor extraction, and fracture enhancement.

5.1 PROGRESSIVE SYSTEM MODIFICATION

At sites where the ground-water contamination covers a broad area it is often necessary to initiate ground-water extraction using numerous widely spaced wells. As the remediation progresses, the outer edges of the contaminant plume will probably be cleaned up first, and the wells that have been located there will become useless. Furthermore, continued operation of these wells will interfere with the progress of the cleanup in the areas that still have contamination. It is, therefore, necessary to turn off these outer wells, and perhaps to increase the rate of withdrawal in the interior of the remaining plume.

An example of this is the Fairchild Semiconductor site, where as many as 14 offsite wells were pumped initially. As the remediation has progressed, the number of offsite extraction wells pumping has been reduced to 5.

Another example is the IBM Dayton site, where up to 17 extraction wells have been used simultaneously to reduce the extent of the contaminant plume leaving the site. Past experience has shown that these wells can probably reduce the size of the plume so that it can be confined within the bounds of the IBM property. Accordingly, a phased reduction in the number of extraction wells is planned so that eventually only one or two onsite wells will be sufficient to control contaminant migration.

5.2 PULSED PUMPING

Pulsed pumping is a technique that has been proposed as a way to increase the efficiency of ground-water extraction systems in situations where the slow release of contaminants from residual sources within the aquifer is controlling the rate of cleanup. These residual sources may be contaminants adsorbed to the aquifer materials or contained in low permeability lenses, or they may arise from the slow dissolution of contaminants from residual NAPLs.

The idea behind the pulsed pumping concept is that, since the rate of mass removal is primarily controlled by the release of residual contaminants rather than by the velocity of ground- water flow, it does no good simply to pump more ground water. By pumping intermittently the ground water passing through the residual source region can be allowed to dissolve or desorb contaminants from it almost to equilibrium while the recovery wells are off. Then, when extraction resumes, the ground-water produced will carry out a higher load of contamination.

None of the case study sites in this investigation have implemented a formal plan for pulsed pumping. At the GenRad site, the extraction wells were turned off in the winter to prevent freezing of the above-ground piping. This might have been expected to result in higher contaminant concentrations in the extracted water when the wells resumed pumping in the spring. Unfortunately, the quarterly sampling frequency used at this site is too low for such a phenomenon to be observed.

At the Utah Power & Light site, the individual wells have been operated intermittently, with production shifting from one well to another. This has been done partly because the productivity of the shallow aquifer is reduced during the winter and spring months by low water levels. In this case, also, the data collection frequency has been too low to determine whether there is any correlation between interrupted pumping and the concentrations produced.

5.3 PHYSICAL CONTAINMENT SYSTEMS

At the Fairchild Semiconductor site a slurry wall was constructed around the Fairchild property in the uppermost contaminated aquifer. The purpose of the wall was to prevent offsite movement of contaminants both by physical intervention in the flow system and by facilitating the reversal of gradients across the site boundaries. As a

result of ground-water extraction inside the slurry wall, the onsite portion of the uppermost aquifer has been dewatered. This has helped to reverse the vertical gradients and prevent the flow of contaminated ground-water to underlying aquifers. It has also prevented flushing of the aquifer materials inside the slurry wall and the collection of ground-water samples there.

5.4 REINJECTION

Reinjection of treated ground water to the aquifer is frequently considered as a means of increasing the velocity of ground-water flow toward the recovery wells. It would also serve as a disposal method for the treated ground water.

Reinjection was used briefly at the IBM Dayton site, where a line of offsite injection wells was intended to increase the rate at which the contaminant plume was drawn back to the site. However, the injection wells rapidly became clogged and had to be dropped from the system.

Reinjection was also considered at the Utah Power & Light site. It was never implemented, however, because the high potentiometric head that would be produced around the injection wells might induce unwanted vertical flow into the lower aquifers.

5.5 VAPOR EXTRACTION

Vapor extraction was used as an enhancement technology at the Ponders Corner and Verona Well Field sites. At Ponders Corner the vapor extraction system was installed at the original contaminant source to remove adsorbed contamination in the vadose zone. No information has been provided on the performance of this vapor extraction system. However, if the main impediment to aquifer cleanup at the Ponders Corner site is the slow release of contaminants from low permeability zones in the saturated part of the aquifer, the effectiveness of the vapor extraction system in speeding up aquifer remediation may be limited.

At the Verona Well Field site, a vapor extraction system has been installed to help in the removal of contaminants from a floating NAPL layer. The vapor extraction system is positioned directly above the ground-water extraction system so that they can both work in concert. In the 22 months between March 1987 and January 1989, the ground-water

extraction system removed an estimated 11,000 pounds of volatile organic compounds (VOCs). During the 10 months between March 1988 and January 1989, the vapor extraction system removed approximately 27,000 pounds of VOCs. Obviously, the vapor extraction system is helping significantly in the removal of volatile contaminants.

At sites with floating layers of volatile contaminants, ground-water and vapor extraction systems can potentially be used together to great advantage. The drawdown produced by the ground-water extraction system thickens the vadose zone so that the vapor extraction system can reach deeper into the aquifer. The vapor extraction system, in turn, reduces the atmospheric pressure above the water table and permits higher ground-water withdrawal rates with the same drawdown because of increased pressure gradient. In addition, if the systems are operated to produce a fluctuating water table, the NAPL saturation of the soil can be kept low. This increases the interfacial area of contact between the NAPLs and the moving water and vapor phases so that the rates of volatilization and dissolution will be increased. It also increases the air and water permeability of the soil in the NAPL-contaminated zone so that contaminant removal can be accelerated. At the Verona Well Field site the tandem operation of the ground-water and vapor extraction systems has not as yet been manipulated to maximize these possibilities.

5.6 FRACTURE ENHANCEMENT

The Black & Decker case study site involved contamination of a fractured rock aquifer in which the fracture density was relatively low. Because of the low fracture density, efforts to establish a hydraulic capture zone in the aquifer by pumping wells were unsuccessful. In order to increase the permeability and interconnectedness of the aquifer, explosives were used to create more thorough fracturing in the vicinity of the ground- water extraction wells. As described in the Black & Decker case study, this technique appears to have made possible the establishment of a capture zone to control contaminant migration in the aquifer.

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APPENDIX A

DENSITIES, SOLUBILITIES, AND MOBILITY CHARACTERISTICS OF ORGANIC HAZARDOUS SUBSTANCES FREQUENTLY FOUND AT PROPOSED AND FINAL NPL SITES[a]

Chemical Name	Frequency[c]	Density[c]	Reference[c]	Solubility[c] (mg/l)	Reference[c]	Koc[d]	Mobility Class[d]
1,1,2-Trichloroethylene (TCE)	331	1.46 - 1.49	1	1.1×10^3	4	152	Moderate
Toluene	259	0.866	1	5.067×10^2	5	242	Moderate
Benzene	218	0.8787	1	1.787×10^3	6	97	High
Chloroform	182	1.474 - 1.478	1	8.216×10^3	7	134	Very High
PCB-1260/PCB-1254[b]	170	1.4 - 1.5	3	7×10^{-1}	8	349,462/63,914	Immobile
1,1,1-Trichloroethane	163	1.3376	1	1.554×10^3	7	155	Moderate
Tetrachloroethene	155	1.58658	1	1.49×10^4	7	318	Moderate
Phenol	124	1.071	1	9.3×10^4	9	27	Very High
Ethylbenzene	120	0.866	1	1.53×10^2	6	622	Low
Xylene (meta-, ortho-, para-)	119	0.86	1	1.46×10^2, 2.13×10^2, 1.85×10^2	10, 11	588, 363, 557	Low, Moderate, Low
1,2-Trans-Dichloroethylene	105	1.28	3	3.9×10^4	12	39	Very High
Methylene Chloride	95	1.307 - 1.361	1	1.37×10^4	7	25	Very High
1,1-Dichloroethane	89	1.1680 - 1.1757	1	5.5×10^3	13	45	Very High
1,1-Dichloroethene	88	1.2129	1	3.2×10^3	14	217	Moderate
Vinyl Chloride	79	1.33 - 1.39	2	1.1	15	22 - 704	Very High-Low
Chlorobenzene	69	1.107	1	4.72×10^2	16	318	Moderate
Carbon Tetrachloride	65	1.589	1	8.00×10^2	17	232	Moderate
1,2-Dichloroethane	65	1.2569	1	8.69×10^3	18	36	Very High
Pentachlorophenol (PCP)	59	1.978	1	1.4×10^1	19	900	Low
Naphthalene	52	0.9628 - 1.162	1	3.1×10^1	20	1,300	Low
Methyl Ethyl Ketone	43	0.805	1	2.68×10^5	21	235	Moderate
Acetone	33	0.788	1	2.3×10^6	12	1	Very High
Phenanthrene	29	1.179	1	1.29	22	23,000	Immobile
Benzo (a) Pyrene	27			4.9×10^{-2}	12	282,185	Immobile
1,1,2-Trichloroethane	25	1.4416	1	4.5×10^3	18	49	Very High
DDT	24	1.241 - 1.306	2	5.0×10^{-3}	13	238,000	Immobile
Anthracene	24	1.25	1	4.5×10^{-2}	13	26,000	Immobile
BHC Gamma	23	--[b]	--	3.14×10^1	12	28,900	Immobile
Bis(2-ethylhexyl)Phthalate	23	0.981	2	4.0×10^{-1}	13	12,200	Slight
1,1,2,2-Tetrachloroethane	22	1.58658	1	2.9×10^3	13	88	High
Styrene	22	0.9059	1	3.2×10^2	10	380	Moderate
Benzo(j,k)Fluorene	20			3×10^0	12	19,800	Slight
Pyrene	19	1.271	1	1.35×10^{-1}	23	63,400	Immobile
1,2-Cis-Dichloroethylene	19	1.28		8.0×10^2	15	124	High
Fluorene, NOS	17	1.202	1	1.98	24	5,835	Slight
Trichlorofluoroethane	15	1.494	1	1.10×10^3	25	159	Moderate
Di-N-Butyl Phthlate	15	1.048	3	1.3×10^1	26	217	Moderate
Chlordane	15	1.59 - 1.63	1	1.85	27	53,200	Immobile
Acenapthene	15	1.189	1	3.7	12	2,580	Slight
Ethyl Chloride	15	0.9214	1	5.74×10^3	13	42	Very High

[a] This table is for illustrative purposes only.

[b] Data unavailable in selected references.

[c] Source: CH2M HILL. Technical Support Document: Revised Hazard Ranking System, EPA Contract 68-01-7090.

[d] Source: CH2M HILL. May 1986. Remedial Investigation, Seymour Recycling Corporation, Volume 2. EPA Contract 68-01-6692

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APPENDIX B
CONTAMINANT PARTITIONING IN SORBING MEDIA

One error commonly made in estimating the initial mass of contaminants present in the saturated zone is to neglect the contaminants sorbed to the solid phase. The contaminants sorbed to the solid phase can recontaminate the liquid phase once remediation has stopped, or they can slow the progress of remediation. The total mass of contaminants present in the saturated zone is given by:

$$M_T = M_L + M_S = R\ C\ n\ V \qquad (1)$$

where M_T = the total mass of contaminants in the saturated zone, M_L = the mass of contaminants in the liquid phase, M_S = the mass of contaminants sorbed to the solid phase, n = the porosity, C = the concentration in the liquid phase in mass of contaminants per volume of water, V = the bulk aquifer volume, and R = the retardation factor. Equation (1) states that the mass of contaminants in the saturated zone is equal to the retardation factor times the mass contained in the liquid phase.

Derivation

The retardation factor, R, is defined as:

$$R = \frac{V_s}{V_c} = 1 + \frac{K_d\ D_b}{n} \qquad (2)$$

where V_s = the average linear velocity of the ground water V_c = the average linear velocity of the contaminants, D_b= bulk soil density, K_d= distribution coefficient.

The distribution coefficient, K_d, is defined as:

$$K_d = S/C, \qquad (3)$$

where S = mass of sorbed contaminants per mass of soil.

The mass of contaminants in the soil, M_s, is given by:

$$M_s = S\ D_b\ V, \qquad (4)$$

and the mass of contaminant in the liquid phase, M_L, is:

$$M_L = C\ n\ V. \qquad (5)$$

Equations (4) and (5) can be combined to give the total mass of contaminants in the two phases:

$$M_T = M_L + M_s = S\ D_b\ V + C\ n\ V \qquad (6)$$

If equation (3) is solved for S, then equation (6) becomes:

$$M_T = (\ K_d\ D_b + n)\ C\ V, \qquad (7)$$

which, after rearrangement, becomes:

$$M_T = (1 + K_d\ D_b/n)\ C\ n\ V \qquad (8)$$

Substitution of equation (2) in equation (8) yields equation (1).

As an example, if the retardation factor in a given soil for a given contaminant is 4, then the mass of contaminants present in the solid phase is 3 times the mass of contaminants present in the liquid phase. That is, the mass of contaminants present in the liquid phase is given by equation (5), and the mass of contaminants sorbed to the solid phase is given by:

$$M_s = (R-1)\ C\ n\ V$$

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